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FOR

HORIZONTAL AND VERTICAL RECEIVER-CONSISTENT DECONVOLUTION FOR AN OCEAN BOTTOM CABLE

INVENTOR:
JAMES E. GAISER

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E. Eugene Thigpen
Signature: E. EUGENE THIGPEN
Date of Signature: October 22, 1997

HORIZONTAL AND VERTICAL RECEIVER-CONSISTENT DECONVOLUTION FOR AN OCEAN BOTTOM CABLE

BACKGROUND OF THE INVENTION

Field of the Invention

This invention is concerned with improving the coupling response of a three-component seismic sensor implanted on the bottom of a body of water. Attention is directed to spectral balancing of the cross-line and vertical sensor response in amplitude and phase, consistent with the geometry of the array as deployed on the water bottom.

Discussion of Relevant Art

Seismic exploration studies often involve use of both compressional wavefields and shear-wave radiation. In marine operations, although compressional waves propagate through the water, shear waves do not because water has no shear strength. Therefore, shear-wave studies, such as used in vertical rock-fracture studies, in a marine environment require use of motion-sensitive sensors, such as geophones, planted on the water bottom using ocean bottom cables (OBC).

Please refer to Figure 1 where a plurality of seismic sensors 10_0, 10_1, 10_2,...,10_i (i=3,4,...,n, where n is an integer) are shown laid on the bottom 12 of a body of water, 14. The sensors are spaced-apart by a desired separation such as 10 meters. The sensors are preferably multiaxial motion-sensitive devices which generate an electrical signal proportional to particle velocity of the water bottom material. The sensors are responsive to seismic waves in

general and in particular to both compressional and shear waves.

The sensors are mechanically and electrically coupled to a sectionalized ocean-bottom cable (OBC) 16 of any well-known type, which may be many kilometers long. The OBC includes communication channels, which may be electrical, optical or ethereal, for transmitting sensor signals to suitable instrumentation mounted in a service vehicle. One or both ends of a cable may be marked by a buoy, such as 18, at the water surface for later recovery. For three-dimensional (3-D) areal surveys, many cables may be laid out side-by side in parallel, perhaps 25 meters apart, in a wide swath.

Usually, the cables and sensors (hereinafter referred to as receivers) are laid out over the area to be surveyed by a cable-tender boat. At some later time, a service ship such as 20, recovers one or more cables, such as 16 from the water bottom. The cable communication channels are connected to recording instrumentation of any desired type, generally shown as 21, installed in the ship 20, for receiving and partially processing seismic signals. The ship is usually equipped with a precision navigation means such as a GPS receiver and may include a radar beacon 22 for ranging on a radar reflector 24 mounted on tail buoy 18 at the other end of cable 16.

An acoustic sound source 26 is fired at each of a plurality of designated source locations distributed over an area of interest. The source location are preferably spaced apart by an integral multiple of the sensor spacings. Source 26 radiates wavefields such as generally shown by 28 and 30 to insonify subsurface earth layers such as 32, whence the wavefield is reflected back towards the surface as reflected wavefield 34. The receivers 10_i intercept the mechanical

earth motions, convert those motions to electrical signals and send those signals through the communication channels to the recording equipment 21 in ship 20.

A wavefield may propagate along a direct travel path such as 36 or along reflected-ray travel paths such as 38, 38′ and 38′′ to the respective receivers 10_i. The recorded data are presented in the form of time-scale traces, one trace per receiver/shot.

A collection of time-scale traces resulting from a single source activation (a shot) that insonifies a plurality of receivers such as in Figure 1, constitutes a common source gather. On the other hand, with reference to Figure 5, a collection of time-scale traces as recorded by a single receiver 10_i after insonification by a plurality of spaced-apart shots 26, 26′, 26′′ constitutes a common receiver gather. The separation between a source and a receiver, is defined as the offset. Typically in 3-D operations ship 20 occupies a convenient central location, interconnected with a plurality of receivers, while a second shooting ship (not shown) actually visits the respective designated survey stations to generate common receiver gathers.

Figure 2 is a close-up, X-ray-like side view of a three-component motion receiver 10_i. The sensitive axes are in-line (x axis), unit 42, cross-line (y axis), unit 44 and vertical (z axis) unit 40. Preferably, the two horizontally-polarized receivers respond to shear waves and the vertical receiver responds to compressional waves.

A 3-component receiver is customarily packaged in a single elongated case. The individual units are gimbal-mounted so as to become automatically aligned along their mutually orthogonal axes after deposition on the sea floor. For good and sufficient reasons, the case containing the

receiver components is usually cylindrical. Cable 16 is relatively heavy. Secured to the fore and aft ends of the elongated receiver case, the cable 16 firmly holds a typical multi-axis receiver unit, 10_i, to the sea floor 12. The in-line receiver component 42 is well coupled to sea floor 12 because of the inherent stability of the elongated case along the in-line direction. That situation in not valid, however, for the cross-line receiver component 44.

Please refer to Figure 3 which is an X-ray-like cross section of multi-component receiver 10_i taken along line 3-3′, looking back towards ship 20. Because of its cylindrical shape, case 10_i not only rolls from side to side as shown by curved arrows 46, but water currents and other disturbances can cause the receiver case to roll and shift laterally in the cross-line direction as shown by arrows 48, 48′. Those disturbances do not affect the in-line receiver components because of their respective polarizations but they do introduce severe noise to the cross-axis signals.

Figure 4 is multi-axis receiver 10_i as viewed from above along line 4-4′ of Figure 2.

A method for correcting poor coupling of a logging sonde in a borehole was described in a paper by J. E. Gaiser et al., entitled Vertical Seismic Profile Sonde Coupling, published in *Geophysics* n. 53, pp 206-214, 1988. Although that method is not directly applicable to 3-D seismic exploration, it is of interest because it demonstrates the evil effects of poor coupling of a sensor to the ground.

There is a long-felt need for a method for measuring and suppressing signal distortion attributable to poor water-bottom coupling of one of the components of an ocean-bottom, cable-mounted, 3-component seismic receiver and for balancing the spectral response of the respective components.

SUMMARY OF THE INVENTION

A computer-aided method for balancing the spectral response characteristics of the vertical and cross-line components of a three-component seismic receiver relative to the in-line component. The method has particular application to three-dimensional seismic surveys. Limits are defined for near-offset source-receiver trajectory vectors in range and azimuth. A plurality of seismic wavefields emanating from near-offset source locations are assembled in a computer matrix to form in-line, cross-line and vertical common receiver gathers of reflection data from within a time window of a preferred length. The respective common receiver gathers are normalized for spherical divergence and said seismic wavefields are transformed from the time domain to the frequency domain. Cross-line and vertical deconvolution operators are generated and applied to the cross-line and the vertical receiver gathers respectively to form a corrected cross-line component. An additional vertical deconvolution operator is generated for minimizing vertical component energy. The vertical deconvolution operator is applied to the vertical receiver gathers to form a corrected vertical component.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features which are believed to be characteristic of the invention, both as to organization and methods of operation, together with the objects and advantages thereof, will be better understood from the following detailed description and the drawings wherein the invention is illustrated by way of example for the purpose of illustration and description only and are not intended as a definition of the limits of the invention:

10/20/97

FIGURE 1 is a conventional view of a ship servicing an ocean-bottom cable to which are coupled a plurality of multi-axis sensors;

FIGURE 2 is an X-ray-like cross section of a three-component seismic receiver;

FIGURE 3 is an end view of the three-axis seismic receiver;

FIGURE 4 is a view of the three axis receiver of FIGURE 2 as seen from above;

FIGURE 5 illustrates the concept of common receiver gathers;

FIGURE 6 is a panel showing a comparison of an in-line gather of seismic signals, a cross-line gather of seismic signals and a gather of vertically-polarized signals;

FIGURE 7 illustrates the criteria for data selection to be used in processing with reference to the shot-receiver layout in the field;

FIGURE 8 is a panel showing the same data as FIGURE 6, after processing by the method of this invention; and

FIGURES 9A AND 9B are flow diagrams showing the data-processing steps taught by this invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Figure 6 is a panel of time scale traces representative of three co-located common receiver gathers, 60, 62 and 64 which display respectively from left to right, in-line, cross-line and vertical geophone signals. Direct water arrivals and strong shear-wave signals appear on the in-line gather, 60, in addition to low-frequency interface waves. The cross-line gather, 62, is very weak although the high-amplitude, low-frequency interface waves are present. The vertical gather, 64, exhibits converted-wave reflections accompanied by the interface waves.

10/20/97

Please refer now to Figure 7. An OBC represented by solid line 66, is laid along a receiver line having an in-line azimuth which happens to be north or 0° for this example. A plurality of 3-component receivers are mounted in cable 66, one of which, 68, is a receiver such as might have been responsible for the common receiver gathers of Figure 6 Receiver 68 contains three mutually orthogonally polarized receivers as previously described, of which one is polarized in-line according to the double-headed arrow 67.

A source advances along a shot line (dashed line 69) parallel to but offset from line 66 by a few tens or hundreds of meters. The source sequentially visits a plurality of designated stations that are uniformly spaced-apart along line 69. Some exemplary stations are shown by small circles 70, 72, 74, 76. For simplicity, only one receiver, 68, from one receiver line 66 is shown. Four source stations chosen at random from along a shot line 69 are shown. A second shot line 73 and source location 75 are also shown. In an actual 3-D seismic survey, many receiver lines and many shot lines would be occupied.

As a source advances along line 69, the source-receiver trajectory vector changes from a virtual in-line geometry, such as between receiver 68 and source station 76, to a direct broadside geometry between receiver 68 and source station 72. The changing geometry is reflected in the response characteristics of the traces of the common receiver gathers of Figure 6. On the in-line panel, the first arrivals and the shear-wave reflections are characterized by high amplitude on all traces except for the four innermost traces at the point of closest source-receiver approach such as would be the case of source station 72 which lies directly opposite receiver 68. At that point, the source-receiver trajectory is essentially

perpendicular to the polarization direction of the in-line receiver. Conversely, since that is the very direction in which the cross-line receiver is polarized, as might be expected, the signals on the innermost traces of the cross-line panel are much stronger than on the outer traces. The vertical panel has a strong component of converted PS waves mixed with interface wave interference.

The objective of this invention is to provide a method for estimating, in the frequency domain, deconvolution operators for removing the coupling responses from the cross-line and the vertical seismic signal components in OBC surveys. The purpose is to balance the spectral response of the respective signal component in amplitude and phase in a manner consistent with the field geometry.

The method proposed to determine the deconvolution operators for the cross-line and the vertical components is by least squares minimization in the frequency domain. For each frequency, a complex coefficient is determined such that the particular equation is minimized. The entire bandwidth of these operators contain the appropriate coupling responses. The approach to be described minimizes the first arrival energy of the transverse component over a reflection time window, containing the early arrivals, that is 500 to 1000 milliseconds long, measured from the first breaks. Early arrivals are preferred because they are less contaminated by noise. The energy in the window is assumed to be predominantly polarized in the vertical plane, even in the presence of azimuthal anisotropy, and thus also in the radial and vertical components. The transverse component is assumed to be relatively devoid of energy in the window of interest. Near-offset data originating from offsets less than about 500-750 meters are normalized for spherical spreading due to varying offsets. Far-offset data, such as

that from source location 76, Figure 7, which lives beyond some preferred limiting offset range defined by arc 71, preferably are not used.

A good model to describe the recorded signals, x′, for an ocean-bottom cable (OBC) survey is given in matrix form by

$$x' = Gx \qquad (1)$$

where the x are actual ground motions and G is a 3×3 matrix of complex valued coupling terms. Expanding (1) yields

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} I & 0 & 0 \\ 0 & C & W \\ 0 & -W & V \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} \qquad (2)$$

where the x motions are oriented in the line direction parallel to the cable, y motions are oriented in the cross line direction perpendicular to the cable and z motions are in the vertical direction. It is assumed that the coupling is perfect in the in-line direction, thus I is unity for the x component. It is also assumed that the cross line and vertical components are imperfectly coupled, given by C and V respectively and that motions about the axis of the cable on the water bottom result in the terms W for the cross-line and the vertical component.

Inverting (2) to recover actual ground motions gives

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \frac{1}{\det|G|} \begin{pmatrix} \det|G| & 0 & 0 \\ 0 & V & -W \\ 0 & W & C \end{pmatrix} \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix}, \qquad (3)$$

where $\det|G| = CV+W^2$ is the determinant. Clearly, the in-line response is $x=x'$ and is uncoupled from the cross-line and vertical response in this formulation. For perfect

coupling, C and V are unity and W is zero. If C and V are not unity and W is not zero and these values are known, we can remove the effects of coupling and obtain the original ground motion. The approach described here uses the in-line response as a reference of the wavefield (but only in the in-line direction) to design deconvolution operators in a least squares energy sense to be adapted to the cross-line and vertical data.

The first step to determine the deconvolution operator is to determine the actual cross-line response. The procedure used here exploits the physics that polarized P-waves and PS-waves for early near-offset arrivals have particle motion predominantly in the source-receiver vertical plane, i. e., the radial vector with respect to the source station of origin. Data to be selected for processing preferable reside within a sector embracing a source-receiver azimuth of $45° \pm \alpha°$ relative to the orientation of the in-line receiver component. Here α is an arbitrary tolerance such as 30°. Referring back to Figure 7, data from shot stations such as 72 and 76 in the shaded zones, outside the so-delimited sectors, are considered to be far offset and not used. For purposes of this disclosure, the near offset has thus been defined in range and azimuth.

The vertical plane contains vertical motion and radial horizontal motion for the direct P-wave, the reflected P and PS waves and the elliptically polarized water sediment interface waves. Radial horizontal motion is obtained by vector rotation of the in-line and cross-line components given by

$$r = \cos(\theta)x + \sin(\theta)y, \tag{4}$$

where the angle θ is the amount of rotation necessary to point the in-line vector, 77, away from the source perpendicular to the wavefront 79 emanating from source

location 70, in the radial direction, angle 78 of Figure 7. The component of the particle motion of these waves perpendicular to the vertical plane (transverse horizontal) is minimal. Transverse horizontal motion normal to the vertical plane is given by the rotation,

$$t = -\sin(\theta)x + \cos(\theta)y. \tag{5}$$

Equation (5) leads to the hypothesis that the summed energy of the transverse horizonal components after transformation to the frequency domain, as given by

$$\Sigma_i \left| -\sin(\theta_i)x_i(\omega) + \cos(\theta_i)y_i(\omega) \right|^2 = \min, \tag{6}$$

is a minimum for each angular frequency ω. Summation i, is over many shots from different directions into a single receiver station and the angle θ_i is the rotation for the ith source. Substituting for x_i and y_i in equation (3) gives

$$\Sigma_i \left| -\sin(\theta_i)x'_i + \cos(\theta_i)\left[c(\omega)y_i' + w(\omega)z_i'\right] \right|^2 = \min, \tag{7}$$

where the complex coefficients to be solved in the least squares sense are $c = V/\det|G|$ and $w = -W/\det|G|$. From equation (7), it is clear that the data used for the analysis are 3-component receiver gathers as in Figure 1.

Expanding equation (7) and differentiating with respect to the complex conjugates of c and w leads to the normal equations

$$\begin{pmatrix} \Sigma_i\cos^2(\theta_i)\, y'_i\overline{y}_i & \Sigma_i\cos^2(\theta_i)\, z'_i\overline{y}_i \\ \Sigma_i\cos^2(\theta_i)\, y'_i\overline{z}_i & \Sigma_i\cos^2(\theta_i)\, z'_i\overline{z}_i \end{pmatrix} \begin{pmatrix} c(\omega) \\ w(\omega) \end{pmatrix} = \begin{pmatrix} \Sigma_i\sin(\theta_i)\cos(\theta_i)\, x'_i\overline{y}_i \\ \Sigma_i\sin(\theta_i)\cos(\theta_i)\, x'_i\overline{z}_i \end{pmatrix} \tag{8}$$

where the bar denotes the complex conjugate of the primed quantities x'_i, y'_i and z'_i.

The next step is to minimize the vertical component response $z(\omega)$ for each frequency because it has the added contribution from the cross-line component. This leads to the least squares problem

10/20/97

$$\sum_i |z_i(\omega)|^2 = \sum_i |-w(\omega)\acute{y}_i + v(\omega)\acute{z}_i|^2 = \min \qquad (9)$$

where w is already known and the coefficient v=C/det|G| must be determined. Expanding (9) and differentiating with respect to the complex conjugate of v, leads to the normal equation

$$v(\omega)\sum_i \acute{z}_i \overline{z}_i = w(\omega)\sum_i \acute{y}_i \overline{z}_i, \qquad (10)$$

where $v(\omega)$ easily can be solved.

After the coefficients $c(\omega)$ and $w(\omega)$ have been determined in a least squares sense for all of the shots contributing to the analysis, the cross-line response is

$$y(\omega) = c(\omega)y'(\omega) + w(\omega)z'(\omega). \qquad (11)$$

The corrected vertical response is given by

$$z(\omega) = -w(\omega)y'(\omega) + v(\omega)z'(\omega), \qquad (12)$$

once the coefficient $v(\omega)$ has been determined.

Figure 8 shows the time scale gathers 61, 63, 65 corresponding to the same three gathers, previously shown in Figure 6, after application of the least-square operators (11) and (12). The cross-line component has been increased in amplitude to approximately match the in-line response but the high-amplitude, low frequency interface wave has been substantially reduced. On the vertical component, much of the converted-wave energy has been reduced but the first break energy and the interface waves are essentially unchanged.

The best mode of operation is best shown from the flow diagram shown in Figures 9A and 9B. For a given receiver and arbitrarily-selected shot stations, a volume of data from co-located, receivers 80, 82 and 84, formatted as common receiver gathers, are entered as an ordered array into a matrix, such as a computer memory 86. For a given

common receiver gather, data are selected from those source locations at 88 that lie within a predetermined range of offsets (the rear offset). Source locations are further limited to those residing within a fan, in an appropriate quadrant, of 45°± some arbitrary tolerance, α, at step 90. Thereafter, a time window of data with predetermined length is selected at step 92 that begins at the water break time, defined for each source-receiver pairing from the known water velocity (at 94), receiver water depth and offset distance. At step 96, the rear-offset data entries are normalized for spherical divergence to provide a 3-component normalized, resolved data block of near-offset early reflected arrivals in the time domain.

Having completed the housekeeping preliminaries, the data block is transformed from the time domain to the frequency domain at step 98. The terms for the normal equations (8) and (10) are determined for each angular frequency at step 100, and added into the appropriate summations. At step 102, the program loops back to 104 to process data from the next source location to be included in the given gather. The program continues iteratively until the data from all of the source locations which meet acceptable criteria have been processed.

Thereupon the program solves for the cross-line and vertical component coupling coefficients in equations (8) and (10) at step 108 for each angular frequency. In the final loop of the program, these coefficients are applied to the entire receiver gather, taken from computer memory 86 (Figure 9B), for all offsets, all source receiver azimuths and all recorded times. For a selected shot, the data are transformed from the time domain into the frequency domain at step 112. The cross-line component is corrected at 114 using equation (11) and the vertical component is corrected

at 116 using equation (12). Finally, the data are transformed into the time domain at 118 before looping back at 120 to select the next shot at 126. The program continues iteratively until the response characteristics for all the cross-line and vertical components have been corrected. Thereupon, the program loops back at 122, selects the next receiver at step 106, and repeats the above steps. The program ends at 124 after all combinations of the source-receiver trajectory vectors have been resolved.

This invention has been described with a certain degree of specificity by way of example but not by way of limitation. Those skilled in the art will devise obvious variations to the examples given herein but which will fall within the scope and spirit of this invention which is limited only by the appended claims.

WHAT IS CLAIMED IS: